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Review Letters

Secondary Students' Visual-Spatial Ability Predicts Performance on the Visual-Spatial Electricity and Electromagnetism Test (VSEEMT)

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Abstract
This study examines the relationship between students' general visual-spatial ability and their understanding of electricity and electromagnetism, a topic that requires imagining many invisible, 3-dimensional phenomena. Participants (N = 428 Singaporean secondary students) completed the Visual-Spatial Ability Test (VSAT) and the Visual-Spatial Electricity and Electromagnetism Test (VSEEMT). Results reveal that students' visual-spatial ability is significantly, positively correlated with their achievement in the VSEEMT; this relationship was highest for students with previously lower ability. Thus, visual-spatial ability is an asset to students in mastering the concepts of electricity and electromagnetism, especially for students of lower ability. The findings support a need for visualization instruction that can support students' visual-spatial ability, which may help them visualize the abstract phenomena and deepen their understanding of the concepts.

Keywords
Visual-spatial ability, Physics education, Visual-Spatial Electricity and Electromagnetism Test (VSEEMT), Rasch model

1. Introduction and Theoretical Background

Students' mental reasoning abilities are predictive of their understanding of many abstract scientific concepts, and supporting students' general reasoning ability may transfer to science-specific learning outcomes that call upon such skills (e.g., Wu & Shah, 2004). One such general ability that may be relevant for science education is visual-spatial reasoning, as understanding abstract scientific concepts requires the ability to imagine and visualize many invisible phenomena (e.g., Hansen, Barnett, MaKinster, & Keating, 2004; Uttal & Cohen, 2012). Visual-spatial ability is defined as the ability to conceptualize, apprehend, encode, and mentally manipulate spatial forms of two-dimensional (2D) as well as three-dimensional (3D) objects (Hegarty & Kozhevnikov, 1999; Kozhevnikov, Motes, & Hegarty, 2007). Visual-spatial ability involves a collection of distinct but correlated skills such as: recognizing, retaining, and recalling orientations, arrangements, and positions in which there is movement of a figure or part of a figure; reading, interpreting, and understanding information presented in images; and presenting thoughts, ideas, and data as images (e.g., Gorgorió, 1998; Linn & Peterson, 1985; Tartre, 1990). The cognitive processing of visual-spatial skills is hypothesized to require translation of lower-level sensory input (whether verbal or visual) into mental imagery, and then higher-level manipulations of such mental imagery (e.g., Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006; Lohman, 1988; Wen, Ishikawa, & Sato, 2011). Drawing upon this theoretical basis, prior work has argued that visual-spatial ability is particularly important for science, technology, engineering, and mathematics (STEM) education, because of the role of 2D and 3D concepts that require students to construct and manipulate mental representations to understand and apply them (Uttal & Cohen, 2012). For example, visual-spatial thinking plays a role in making sense of problems (e.g., Owens & Clements, 1998), aiding students' problem-solving abilities (e.g., Kozhevnikov, Motes, & Hegarty, 2007), and understanding scientific concepts (e.g., Black, 2005; Kali & Orion, 1996).

Physics in particular is a visual science. Historically, there is much evidence that mental imagery plays a central role in physics conceptualization processes and in scientific discoveries (Miller, 1984; Rieber, 1995), with examples from physics including Faraday's visualization of lines of force, Maxwell's laws, and Einstein's theory of relativity. Thus, visual-spatial ability also likely plays an important role in students' physics learning and problem solving (Kozhevnikov, Motes, & Hegarty, 2007; Kozhevnikov & Thornton, 2006). Despite this congruence, relatively little research has been conducted on visual-spatial ability in physics education (Kozhevnikov, Motes, & Hegarty, 2007) as compared to other STEM disciplines such as earth and space sciences or chemistry (Uttal & Cohen, 2012). Furthermore, little or no attention has been devoted to understanding the role of visual-spatial skills in more advanced topics within physics that are characteristically abstract and three-dimensional, such as electricity and electromagnetism (E&M).

To address this gap, this study examines the relationship between students' general visual-spatial ability and their understanding of E&M. Moreover, to understand possible differences for students of differing overall physics achievement, the relationship between visual-spatial ability and students' performance in E&M is compared for students achieving low, medium, or high scores in the course. Thus, the research question for the study is: How is visual-spatial ability associated with performance in electricity and electromagnetism, after accounting for other variables i.e., school level and overall physics achievement?

2. Methodology

2.1. Context and Participants

The study was conducted in Singapore. Singapore schools are typically organized into three levels: primary schools with grades 1-6; secondary schools with grades 7-10; and "junior colleges" with grades 11-12. At the end of each level, students take a high-stakes examination that influences their placement at the next level into a school and, within that school, into an academic stream (see Singapore Ministry of Education, 2013a; 2013b). Acceptance to secondary schools and junior colleges is very competitive, and there is significant variation across schools in their students' average performance. Grade 12 students are difficult to recruit for research studies as they are busy preparing for the high-stakes examination for entry to university. So, students at grades 10 and 11 are the focus of study. At the time of data collection, E&M topics were introduced in grade 10 and completed in grade 12, but were not taught explicitly in grade 11. An intact-class sampling technique is used. Schools were randomly selected. Within each school, the physics teachers identified intact classes at grades 10 or 11 to participate in the study according to the class schedule during the data collection period. The participating classes were typical of the students enrolled in mathematics and science courses, based on information provided by the teachers. The investigator administered the study questionnaires to the students during class time.

The sample consists of 233 grade 10 students (121 females and 112 males; aged 16 to 17 years) from eight different classes of two independent secondary schools and 195 grade 11 students (94 females and 101 males; aged 17 to 18 years) from nine different classes of two government schools. All the students were in either "Normal Academic" or "Express" streams, and were pursuing a core set of studies in "mathematics and sciences" (Singapore Ministry of Education, 2013a; 2013b) and likely to pursue a science, technology, engineering, or mathematics (STEM) degree in university.

2.2. Instruments

The instruments for the study include a demographic questionnaire, the Visual-Spatial Electricity and Electromagnetism Test (VSEEMT; Lyna, 2008), and the Visual-Spatial Ability Test

(VSAT). The VSEEMT combines substantial conceptual knowledge of basic electricity (e.g., electrostatics, current, and potential difference in circuits) and electromagnetism (e.g., magnetic effect of a current, force on a current-carrying conductor) with mental manipulation of spatial representations of these concepts. Visualization of 2D and 3D models in the spatial domain are required to answer VSEEMT questions (e.g., mental manipulation to identify identical circuits, visualizing force on a charged particle moving in a magnetic field). The VSEEMT consists of 15 multiple-choice questions and 15 open-ended questions comprising 32 sub-questions, for a total of 47 items. Some items were adapted from O-Level Classified Science (Physics) (Chew, 2000), O-Level Classified Physics (Chew, 2002), The Physical Universe (Krauskopf & Beiser, 1991), Physics Insights for Secondary 3 and 4 (Loo, Loo, & See Toh, 2000), and GCE 'O' Level (Pure) Physics (Yearly) (Wong, 2003). In considering the VSEEMT's validity, the content of the test drew upon existing instruments for secondary physics and was reviewed by the authors and participating teachers to make sure that the topics have been taught and were aligned with the Singapore physics curriculum. Additionally, teachers reviewed whether the VSEEMT required students to engage substantially with visual-spatial thinking skills in addition to the physics content knowledge. Internal consistency of the VSEEMT was tested with a pilot study with secondary and junior college students (Lyna, 2008), with observed Cronbach's alpha for secondary students and junior college students of 0.81 and 0.75, respectively, indicating moderate to high internal consistency and reliability (DeVellis, 2012). Reliability for this study is based on the Rasch model (see next section). Students had 60 minutes to answer the VSEEMT questions.

The VSAT is a test of general visual-spatial ability. Its items are adapted from The Assessment of Ability in Science (ESTEAM) (Perryman & Purcell, 1983) and the National Foundation for Educational Research in England and Wales (1973) – Spatial Test 2 (Three-Dimensional) (Watts, Pidgeon, & Richards, 1973) and Spatial Test 3 (Newcastle Spatial Test) (Smith & Lawes, 1973). A total of 201 items examine twelve interrelated visual-spatial skills:

1. Turn About—recognizing mirror images of a given 2D shape (17 items);

2. Cut Outs—visualizing the folding of 2D shapes into 3D figures (10 items);

3. Jig Cubes—estimating how many 3D cubes of size A are required to make 3D cubes of size B (18 items);

4. 3D Views—identifying alternative perspective on a given object without alternations (16 items);

5. Shapes and Models—identifying 3D figures that can be made from a given 2D shapes after some cuts and folds (20 items);

6. Square Completion—turning round and/or turning over 2D shapes simultaneously (20 items);

7. Block Building—estimating how many of two types of blocks (B and C) are needed to build a large block A (20 items);

8. Object Sections—choosing the solid object which fits each set of drawings showing cross sections of the object's 'end, middle, end' (10 items);

9. Object Plans—choosing the correct top-down view of a model four drawings next to each model made of blocks that shows the view of the model looking down on it from above (10 items);

10. Cross Sections—imagining a view of an object if cut along some arbitrary plane within the object (20 items);

11. Block Construction—estimating how many times a model's face should be used to build a larger model (20 items); and

12. Match Box Corners—identifying and placing a black dot into the common corner of a box after various rotations (20 items).

All twelve parts of the VSAT are used in this study because they together measure the broad variety of visual-spatial skills that are required to perform a complex sequence of mental manipulations, such as rotating; folding; arranging location, position, and direction; turning round and turning over; estimating; recognizing sequences, configuration, location, and position. A variety of visual-spatial thinking skills may be involved in answering electricity and electromagnetism questions related to these skills, such as:

- To mentally rotate the circuit diagrams in order to identify whether the diagrams illustrate identical circuits, visual-spatial skills such as rotating, turning round, and turning over are required

- To visualize the 3D configuration using Fleming's left hand rule in order to decide the direction of force, velocity of charged particle, magnetic field, or current, students need visual-spatial skills such as rotating, arranging location, position, and direction.

- To mentally predict the effect on size, shape, and direction of the electron beam's path that would be produced by the changes of magnetic field or the velocity of the electron, visual-spatial skills such as estimating, recognizing sequences, configuration, location, and position are helpful.

The VSAT consists entirely of short, multiple-choice pictorial items; so, students are able to answer all items very quickly, with all students finishing within the 45-minute period and most students finishing within 25 minutes. By drawing on these twelve sets of skills, the VSAT benefits from the content and substantial validity of these established spatial reasoning instruments. In a pilot study, the internal consistency of the VSAT was tested, with Cronbach's alpha coefficients for secondary students and junior college students of 0.99 and 0.97, respectively, indicating very high internal consistency. Reliability for this study is based on the Rasch model (see next section).

2.3. Data Analysis

Prior to analyses, the data for the study were prepared using a Rasch measurement model, a probabilistic approach to test theory (Bond & Fox, 2007; Liu, 2010). The Rasch model provides significant benefit over analyses using raw data because it accounts for varying difficulties among test items when estimating students' ability with respect to the same items. Furthermore, the Rasch model allows comparisons of items and persons on the same scale. For the present analysis, all VSAT and VSEEMT items were entered as dichotomous data (0 = incorrect, 1 = correct) and analyzed using a dichotomous Rasch model. To simplify interpretation, ability estimates for students were prepared with similar range as the raw data: VSAT with mean of approximately 100 points; and VSEEMT with mean of approximately 50 points. All Rasch models were estimated using the WINSTEPS software package (Linacre, 2007). In Rasch measurement modeling, items are examined for their degree of fit between the students' responses and the proposed measurement model (Bond & Fox, 2007). As a probabilistic model, some amount of variation in students' responses is expected even if the hypothetical measurement model were taken to be true. A mean-square statistic for fit is used, where 1 represents the expected amount of variation, and an acceptable range is 0.7-1.3 (either information-weighted infit or unweighted outfit). Additionally, a z-score on this fit is expected to be near 0, with an acceptable range of -2 to +2. Rasch analyses reveal good fit for the data to the model. For VSAT, the average item infit and outfit mean-squares are 0.99 and 1.16, respectively, with average item infit and outfit z-scores of -0.5 and -0.1. For VSAT, the average person infit and outfit mean-squares are also 0.99 and 1.16, with average infit and outfit z-scores of -0.3 and 0.1. For VSEEMT, the item infit and outfit mean-squares were 0.99 and 1.05, and infit and outfit z-scores of 0.0 and 0.1. The person infit and outfit mean-squares were 1.00 and 1.05, and z-scores of -0.2 and 0.0. These values indicate good overall fit of the item and person estimates with the measurement model for both the VSAT and VSEEMT. Furthermore, the separation reliability for person estimates were also high, 0.96 for VSAT and 0.86 for VSEEMT. Wright maps for both the VSAT and VSEEMT are shown in the appendix, showing the distribution of the estimates of students' abilities and items' difficulties. Taken together, this indicates that the two scales have good fit among the items in measuring the latent trait, and that persons can be reliability differentiated using both scales. Descriptive statistics for students' ability estimates for VSAT and VSEEMT are shown in Table 1.

After preparing data with the Rasch model, analyses are conducted on the Rasch ability estimates for both VSEEMT and VSAT. To understand how VSAT and VSEEMT are related, it is important to separate other effects that may be related to one or both of these variables. For example, VSAT or VSEEMT may be related to students' grade level, a proxy for age and maturation (treated as a dichotomous variable, 0 for grade 10, 1 for grade 11). This can be controlled using partial correlation. Additionally, VSEEMT may be related to students' overall physics per-

Table 1. *Means and standard deviations for the Rasch-estimated variables VSAT and VSEEMT*

Grade Level	VSEEMT	VSAT
Total (n = 428)	46.88 (9.68)	100.04 (14.41)
Grade 10 (n = 233)	52.16 (8.11)	98.10 (16.63)
Grade 11 (n = 195)	40.57 (7.34)	102.35 (10.79)

formance and their prior academic achievement. For overall physics performance, results are compared by splitting the sample into three ability groups based on the final physics course scores: the lower 25%, the middle 50%, and the upper 25%. For prior academic achievement, this may be related to school membership—because of the relationship between prior academic performance and students' admission to differing secondary school or junior college in Singapore—so results are compared across schools.

3. Results

As expected, the students' VSAT and VSEEMT ability estimates were associated with grade level ($r = 0.147$, $p < .01$ with VSAT; $r = -0.597$, $p < .01$ with VSEEMT); this supports the decision to use partial correlation for subsequent analyses of the relationship between VSAT and VSEEMT ability. The partial correlation results reveal that there is a statistically significant, positive correlation between VSAT and VSEEMT (partial $r = 0.226$, $df = 425$, $p < .001$), indicating that students' visual-spatial ability is associated with their performance on the electricity and electromagnetism items, after accounting for the differences in grade level.

In addition to the finding for the entire sample, it is important to determine if this relationship holds when accounting for other factors like overall physics performance and prior achievement. Table 2 shows the means and standard deviations for the VSEEMT and VSAT ability estimates by students' total physics performance and their school membership. For overall physics performance, there is a statistically significant difference for VSEEMT ($F = 8.241$, $df1 = 2$, $df2 = 425$, $p < .001$), but not among VSAT scores ($F = 2.871$, $df1 = 2$, $df2 = 425$, $p > .05$). Additionally, there is a statistically significant difference across schools for both VSEEMT ($F = 99.320$, $df1 = 3$, $df2 = 424$, $p < .001$) and VSAT ($F = 23.211$, $df1 = 3$, $df2 = 424$, $p < .001$).

In recognition of such significant differences in VSEEMT, it is important to consider how the correlation between VSAT and VSEEMT may also vary among students across these distinctions. There is a significant correlation between VSAT and VSEEMT for students in each of the four schools (see again Table 2). Furthermore, when split according to overall ability based on previous exam scores, this association persists, with the strongest correlation among the low ability group, and the weakest correlation among the middle ability group.

Table 2. *Descriptive statistics on VSEEMT and VSAT ability estimates by students' prior achievement and school membership*

Source	VSEEMT	VSAT	VSAT-VSEEMT correlation
Total Physics Performance			
Lower (N=95)	43.44 (9.06)	96.93 (15.90)	.31 **
Middle (N=215)	47.56 (9.71)	100.94 (13.08)	.15 *
Higher (N=118)	48.40 (9.52)	100.89 (15.22)	.21 *
School			
School 1 (N=121)	49.80 (8.81)	104.59 (17.12)	.46 **
School 2 (N=112)	54.70 (6.41)	91.09 (12.87)	.27 **
School 3 (N=96)	42.69 (6.23)	102.26 (11.28)	.30 **
School 4 (N=99)	38.51 (7.77)	102.43 (10.36)	.24 *

Note. For Total physics performance, these are partial correlations after accounting for grade level. For school, these are correlations (participating schools contain either only grade 10 or grade 11).
* p<.05, ** p<.01

4. Discussion

This study is among the first to explore the relationship between students' visual-spatial ability and their conceptual understanding of E&M. This significantly expands on previous work that has explored this relationship in other science disciplines (e.g., Black, 2005; Hegarty, Keehner, Khooshabeh, & Montello, 2009; Wu & Shah, 2004) and in more elementary physics topics such as force and motion (e.g., Kozhevnikov, Motes, & Hegarty, 2007). The significant positive correlation observed between VSAT and VSEEMT demonstrates the importance of the general skill of visual-spatial ability in understanding E&M concepts. Furthermore, these effects were consistent for students of all ability groups, with the strongest relationship among the lower ability students than among medium and higher ability students. This is consistent with findings of previous studies that show how visual-spatial ability is particularly important among novices but less so with increasing domain knowledge (e.g., Uttal & Cohen, 2012). Further research is warranted to address these initial findings. For example, subsequent experimental studies may examine possible causal relations between training on visual-spatial ability and students' performance in electricity and electromagnetism.

The findings also have implications for science teaching. In particular, the results suggest the potential value of explicit training to develop students' visual-spatial ability (Sorby, 2009), particularly for lower-performing students. For example, training exercises for students to use those habits of thought may prove helpful for their overall performance in concepts that rely on visualization about these abstract concepts. Instruction may also draw upon a variety of visualization aids to support students, for example by incorporating animations, simulations, real-time data displays, and physical models. If students are truly to adopt visual-spatial thinking to link with visual-spatial physics, teaching and instruction must give them sufficient experience in using the visual-spatial skills. Thus, science curriculum developers, instructional designers, teachers, teacher trainers, and researchers need to be aware of the link and interdependence between both of them. Science curriculum developers and instructional designers need to incorporate more curriculum activities that would touch on important skills of visual-spatial thinking throughout the topics of electricity and electromagnetism.

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Appendix

Figure 1
Wright map of Rasch estimates for student abilities and item difficulties for the VSEEMT. Students are displayed along the left side of the vertical axis; items are displayed along the right side of the axis.

```
      persons MAP OF items
              <more>|<rare>
  90                +  EM13d
                    |
                    |  EM11a
                    |
                    |
                 .  |
  80                +
                    |T
                    |
                    |  EM2
                    |  EM11biii
                    |  EM1b      EM3
  70             .  +  EM11bii
                 .  |
                 . T|
                .#  |
                ##  |S
               .##  |  EM4c
  60          .###  +  EM13c
             .####  |  EM4b
          ######## S|  EM10a     EM12b
             .####  |  EM11      EM11bi
             .####  |  EM12      EM13a     EM6a
          .#######  |
  50            .#  +M EM10      EM9
        ##########  |  EM7b
             ##### M|  EM14a     EM14b     EM9b
            .#####  |  EM15      EM8a
        ##########  |  EM13      EM7c      EM9a
             .####  |  EM1       EM2ci     EM2cii    EM4       EM5
  40    .#########  +  EM12a     EM2b      EM4a      EM5a      EM7
               ###  |  EM13b     EM1a      EM2a      EM3a
                .# S|S
           .######  |
               .##  |  EM14
                .#  |  EM7a      EM8
  30            ##  +
                .# T|  EM6
                 #  |
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  20                +
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  10                +
              <less>|<frequ>
EACH '#' IS 4.
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Figure 2
Wright map of Rasch estimates for student abilities and item difficulties for the VSAT. Students are displayed along the left side of the vertical axis; items are displayed along the right side of the axis.

```
         persons MAP OF items
                <more>|<rare>
 140                  +
                 .    |
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 130                  +
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                 .    |
 120            .##   +
               .###   |
                .##   |
            .###### S|
               .###   |
           .########  |
 110       #########  +   C8a
          .#########  |
          ##########  |   C8b
            .######   |
              #####   |T  J10
            .######   |   K7
 100       .####### M+    H3    K16
              #####   |   D6b
               ####   |
               ####   |   G16   G20   J3    K19
               .###   |   D2a   G17   J14   J8    K8
               ####   |S  G18   G8    J15   J16   J19   J2    K10   K12   K15   K17   L16
  90           .###   +   C3a   F19   F20   G12   G14   G19   G6    I6    J12   J18   J20   J5
                          J6    K11   K14   K18   K20   K5    K6
                ###   |   F14   F17   G4    G7    H10   I7    I9    J11   J17   J4    K13   K3
                          K4    K9
              .####   |   C7b   C9b   F13   G15   G2    G3    H1    H2    H5    I5    I8    J1
                          J13   J7    J9    K1    K2    L11   L13   L15   L20
              .#### S|    C3b   G11   G5    H6    I10   I2    I3    L10   L12   L14   L18   L19
                          L2    L5
            .######   |   D5a   D6c   F16   H8    H9    I1    I4    L1    L17   L3    L4    L6
                          L7    L8
              .####   |   F7    G10   G13   G9    H7    L9
  80             .#   +M  B10   C7a   C9a   H4
                 .#   |   A17   C1a   F18   G1
                .##   |   F12   F6
                 ##   |   C1b   C6b   E14   F10   F11   F4
                 .#   |   A15   B9    D3a   D6a   E18   E19   E3    F15   F3    F8    F9
                  # T|    A16   A2    A3    B4    B7    E20   E5    F2
  70              .   +   A12   A13   B5    B8    D4b   D5b   E13   E16   F5
                      |S  C6a   D3b   E17   E4    E7
                  .   |   A1    A6    A9    B6    C4a   D4a   E11   E12
                  .   |   A11   A8    C4b   E8
                      |   A10   A14   A5    B1    B3    D2c   D4c   E15   E6    E9    F1
                      |   D1c   D2b   E10   E2
  60              .   +   A4    D1b   E1
                  .   |   A7    C5a
                      |T
                      |   B2    C2b    C5b    D1a
                      |   C2a
                      |
  50              .   +
                <less>|<frequ>
EACH '#' IS 3.
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Supplementary Table 1. *Item fit statistics for each of the VSAT items*

ITEM	RAW SCORE	COUNT	MEASURE	MODEL SE	INFIT MNSQ	INFIT ZSTD	OUTFIT MNSQ	OUTFIT ZSTD
1	397	428	66.35	2.04	1.12	0.90	1.35	0.90
2	383	428	71.34	1.76	1.19	1.60	1.76	2.10
3	380	428	72.25	1.72	1.18	1.60	1.57	1.70
4	410	428	59.58	2.58	1.07	0.40	1.34	0.70
5	402	428	64.10	2.20	1.00	0.00	1.88	1.70
6	397	428	66.35	2.04	1.18	1.20	2.16	2.30
7	411	428	58.90	2.65	1.05	0.30	0.75	-0.30
8	399	428	65.49	2.10	1.15	1.00	1.65	1.40
9	395	428	67.16	1.99	1.14	1.00	1.64	1.50
10	404	428	63.10	2.28	1.07	0.50	1.18	0.50
11	400	428	65.04	2.13	1.12	0.80	1.83	1.70
12	389	428	69.38	1.86	1.08	0.70	1.57	1.50
13	388	428	69.73	1.84	1.19	1.50	1.34	1.00
14	405	428	62.57	2.32	1.06	0.40	0.94	0.00
15	377	428	73.11	1.68	1.22	2.00	1.45	1.50
16	384	428	71.03	1.77	1.22	1.80	1.83	2.20
17	355	428	78.51	1.48	1.49	5.10	1.99	3.70
18	405	428	62.57	2.32	1.20	1.10	1.90	1.60
19	416	428	54.82	3.10	1.09	0.40	1.62	1.00
20	403	428	63.61	2.24	1.32	1.80	2.68	2.70
21	383	428	71.34	1.76	1.37	2.90	2.51	3.60
22	388	428	69.73	1.84	1.31	2.30	1.79	2.00
23	398	428	65.93	2.07	1.20	1.30	1.84	1.80
24	384	428	71.03	1.77	1.38	3.00	2.02	2.60
25	387	428	70.06	1.82	1.25	2.00	3.78	5.10
26	375	428	73.67	1.65	1.34	3.00	2.45	3.90
27	345	428	80.60	1.41	1.39	4.40	2.52	5.70
28	354	428	78.73	1.47	1.45	4.80	2.00	3.80
29	373	428	74.21	1.63	1.43	3.80	2.55	4.20
30	417	428	53.82	3.23	1.03	0.20	3.57	2.30
31	415	428	55.74	2.99	1.05	0.30	1.70	1.10
32	295	428	89.23	1.24	1.58	7.80	1.85	5.70
33	319	428	85.37	1.30	1.64	7.80	2.16	6.00
34	397	428	66.35	2.04	1.23	1.50	1.67	1.50
35	400	428	65.04	2.13	1.19	1.20	1.63	1.40
36	411	428	58.90	2.65	1.07	0.40	1.91	1.40
37	415	428	55.74	2.99	1.03	0.20	1.91	1.30
38	392	428	68.31	1.92	1.15	1.10	1.99	2.30
39	370	428	74.99	1.60	1.17	1.70	1.43	1.60
40	347	428	80.19	1.43	1.42	4.70	1.94	3.90
41	315	428	86.04	1.29	1.43	5.60	1.61	3.70
42	147	428	109.36	1.18	1.35	6.30	2.02	6.30
43	173	428	105.85	1.15	1.44	8.00	2.04	7.50
44	351	428	79.37	1.45	1.42	4.60	1.78	3.20
45	310	428	86.87	1.28	1.51	6.70	1.61	3.80
46	415	428	55.74	2.99	0.98	0.00	1.35	0.70
47	410	428	59.58	2.58	1.01	0.10	1.47	0.90
48	408	428	60.86	2.47	1.08	0.50	1.29	0.70
49	263	428	93.90	1.18	1.66	9.60	2.11	8.60
50	407	428	61.45	2.41	1.05	0.30	1.69	1.30
51	403	428	63.61	2.24	1.01	0.10	1.28	0.70

ITEM	RAW SCORE	COUNT	MEASURE	MODEL SE	INFIT MNSQ	INFIT ZSTD	OUTFIT MNSQ	OUTFIT ZSTD
52	379	428	72.54	1.70	1.12	1.10	1.44	1.40
53	390	428	69.03	1.88	1.13	1.00	1.31	0.90
54	397	428	66.35	2.04	1.15	1.10	2.40	2.70
55	389	428	69.38	1.86	1.16	1.20	1.70	1.80
56	405	428	62.57	2.32	1.11	0.60	2.60	2.50
57	328	428	83.80	1.34	1.67	7.80	2.49	6.70
58	386	428	70.39	1.81	1.22	1.80	2.29	3.00
59	375	428	73.67	1.65	1.16	1.50	1.74	2.30
60	231	428	98.25	1.15	1.74	9.90	2.14	9.50
61	332	428	83.08	1.35	1.48	5.70	1.81	4.00
62	410	428	59.58	2.58	0.82	-0.90	0.34	-1.40
63	408	428	60.86	2.47	0.86	-0.70	0.51	-1.00
64	374	428	73.94	1.64	1.03	0.30	1.05	0.30
65	392	428	68.31	1.92	0.92	-0.60	0.72	-0.70
66	383	428	71.34	1.76	1.07	0.70	1.44	1.40
67	404	428	63.10	2.28	0.84	-0.90	0.40	-1.50
68	390	428	69.03	1.88	0.93	-0.50	0.86	-0.30
69	401	428	64.58	2.17	0.83	-1.10	0.45	-1.40
70	405	428	62.57	2.32	0.85	-0.90	0.59	-0.80
71	406	428	62.02	2.37	0.88	-0.70	0.48	-1.10
72	396	428	66.76	2.02	0.94	-0.40	0.80	-0.40
73	396	428	66.76	2.02	0.93	-0.50	0.63	-0.90
74	389	428	69.38	1.86	0.96	-0.30	1.00	0.10
75	372	428	74.47	1.62	1.03	0.40	1.60	2.00
76	405	428	62.57	2.32	0.87	-0.70	0.71	-0.50
77	385	428	70.71	1.79	0.97	-0.20	1.01	0.10
78	394	428	67.55	1.97	0.90	-0.70	0.82	-0.40
79	378	428	72.83	1.69	1.03	0.30	1.55	1.70
80	379	428	72.54	1.70	1.04	0.40	1.43	1.40
81	380	428	72.25	1.72	1.07	0.70	1.65	2.00
82	402	428	64.10	2.20	0.81	-1.20	0.46	-1.40
83	383	428	71.34	1.76	1.01	0.20	1.16	0.60
84	377	428	73.11	1.68	1.05	0.50	1.53	1.70
85	367	428	75.74	1.57	1.09	0.90	1.40	1.50
86	387	428	70.06	1.82	0.97	-0.20	1.48	1.40
87	360	428	77.40	1.51	1.20	2.10	1.56	2.20
88	336	428	82.34	1.37	1.37	4.40	2.01	4.60
89	378	428	72.83	1.69	0.97	-0.30	1.04	0.20
90	375	428	73.67	1.65	1.08	0.80	1.85	2.60
91	371	428	74.73	1.61	0.95	-0.50	0.90	-0.30
92	372	428	74.47	1.62	0.93	-0.70	1.00	0.10
93	361	428	77.17	1.52	1.08	0.90	1.25	1.10
94	310	428	86.87	1.28	1.31	4.20	1.70	4.30
95	303	428	87.99	1.26	1.38	5.20	1.58	3.90
96	379	428	72.54	1.70	0.87	-1.20	0.92	-0.20
97	332	428	83.08	1.35	1.19	2.50	1.51	2.70
98	305	428	87.67	1.26	1.16	2.30	1.10	0.80
99	354	428	78.73	1.47	0.99	0.00	0.95	-0.20
100	289	428	90.14	1.22	1.26	3.90	1.51	3.90
101	285	428	90.74	1.22	1.34	5.10	1.46	3.60
102	356	428	78.30	1.48	0.76	-3.10	0.59	-2.20
103	310	428	86.87	1.28	1.00	0.00	0.92	-0.60

ITEM	RAW SCORE	COUNT	MEASURE	MODEL SE	INFIT MNSQ	INFIT ZSTD	OUTFIT MNSQ	OUTFIT ZSTD
104	315	428	86.04	1.29	0.99	-0.20	0.99	0.00
105	305	428	87.67	1.26	0.99	-0.20	0.96	-0.30
106	323	428	84.68	1.32	0.96	-0.60	0.92	-0.50
107	295	428	89.23	1.24	1.09	1.50	1.10	0.80
108	303	428	87.99	1.26	1.00	0.00	0.89	-0.90
109	277	428	91.91	1.20	1.11	1.70	1.02	0.20
110	339	428	81.77	1.38	0.81	-2.60	0.66	-2.10
111	337	428	82.15	1.37	0.83	-2.40	0.83	-1.00
112	317	428	85.71	1.30	0.91	-1.40	1.11	0.80
113	285	428	90.74	1.22	0.97	-0.40	0.87	-1.10
114	338	428	81.96	1.38	0.81	-2.70	0.61	-2.50
115	286	428	90.59	1.22	1.06	1.00	0.97	-0.20
116	314	428	86.21	1.29	0.88	-1.90	0.83	-1.20
117	250	428	95.69	1.17	1.11	2.00	1.08	0.90
118	270	428	92.91	1.19	1.03	0.50	0.93	-0.60
119	282	428	91.18	1.21	1.01	0.10	0.90	-0.90
120	286	428	90.59	1.22	1.00	-0.10	0.90	-0.90
121	259	428	94.46	1.18	1.09	1.50	1.08	0.80
122	313	428	86.37	1.28	0.84	-2.50	0.96	-0.20
123	310	428	86.87	1.28	0.72	-4.60	0.61	-3.30
124	223	428	99.30	1.15	1.06	1.20	1.05	0.60
125	346	428	80.40	1.42	0.64	-5.30	0.41	-3.90
126	312	428	86.54	1.28	0.76	-3.90	0.72	-2.20
127	321	428	85.03	1.31	0.71	-4.50	0.61	-2.90
128	336	428	82.34	1.37	0.67	-5.10	0.49	-3.60
129	332	428	83.08	1.35	0.69	-4.80	0.54	-3.30
130	333	428	82.90	1.36	0.66	-5.20	0.54	-3.20
131	298	428	88.77	1.24	0.90	-1.70	1.01	0.10
132	330	428	83.44	1.34	0.67	-5.20	0.57	-3.10
133	324	428	84.51	1.32	0.68	-5.10	0.61	-2.80
134	325	428	84.33	1.32	0.61	-6.40	0.46	-4.40
135	329	428	83.62	1.34	0.65	-5.50	0.48	-3.90
136	313	428	86.37	1.28	0.68	-5.40	0.57	-3.60
137	291	428	89.84	1.23	0.85	-2.50	0.83	-1.40
138	298	428	88.77	1.24	0.79	-3.40	0.74	-2.30
139	311	428	86.70	1.28	0.70	-4.90	0.66	-2.80
140	300	428	88.46	1.25	0.79	-3.50	0.79	-1.80
141	323	428	84.68	1.32	0.67	-5.40	0.57	-3.30
142	312	428	86.54	1.28	0.69	-5.10	0.67	-2.60
143	273	428	92.49	1.20	0.85	-2.60	0.94	-0.60
144	252	428	95.42	1.17	0.88	-2.20	0.80	-2.20
145	301	428	88.30	1.25	0.63	-6.60	0.53	-4.50
146	292	428	89.69	1.23	0.72	-5.00	0.72	-2.60
147	291	428	89.84	1.23	0.74	-4.60	0.82	-1.60
148	308	428	87.19	1.27	0.59	-7.20	0.43	-5.40
149	267	428	93.34	1.19	0.77	-4.20	0.72	-3.00
150	307	428	87.35	1.27	0.61	-6.90	0.45	-5.20
151	196	428	102.83	1.14	1.13	2.60	1.12	1.20
152	304	428	87.83	1.26	0.62	-6.70	0.50	-4.70
153	285	428	90.74	1.22	0.68	-6.00	0.58	-4.40
154	308	428	87.19	1.27	0.57	-7.80	0.40	-5.80
155	267	428	93.34	1.19	0.81	-3.50	1.03	0.30

ITEM	RAW SCORE	COUNT	MEASURE	MODEL SE	INFIT MNSQ	INFIT ZSTD	OUTFIT MNSQ	OUTFIT ZSTD
156	277	428	91.91	1.20	0.67	-6.30	0.58	-4.60
157	275	428	92.20	1.20	0.73	-5.10	0.85	-1.50
158	299	428	88.62	1.25	0.57	-7.90	0.48	-5.20
159	293	428	89.54	1.23	0.60	-7.50	0.49	-5.20
160	277	428	91.91	1.20	0.68	-6.10	0.73	-2.80
161	289	428	90.14	1.22	0.56	-8.60	0.45	-6.00
162	307	428	87.35	1.27	0.62	-6.60	0.52	-4.40
163	307	428	87.35	1.27	0.62	-6.60	0.45	-5.20
164	299	428	88.62	1.25	0.65	-6.30	0.49	-5.10
165	303	428	87.99	1.26	0.62	-6.80	0.45	-5.30
166	295	428	89.23	1.24	0.66	-6.10	0.51	-4.90
167	293	428	89.54	1.23	0.66	-6.10	0.53	-4.80
168	205	428	101.66	1.14	0.90	-2.00	0.81	-2.10
169	271	428	92.77	1.19	0.72	-5.20	0.70	-3.30
170	297	428	88.93	1.24	0.67	-5.90	0.58	-4.00
171	284	428	90.89	1.22	0.69	-5.70	0.60	-4.10
172	295	428	89.23	1.24	0.67	-6.00	0.54	-4.50
173	283	428	91.03	1.21	0.66	-6.30	0.54	-4.90
174	298	428	88.77	1.24	0.65	-6.20	0.51	-4.90
175	288	428	90.29	1.22	0.72	-5.10	0.65	-3.40
176	282	428	91.18	1.21	0.73	-5.00	0.67	-3.40
177	221	428	99.57	1.15	0.86	-2.90	0.85	-1.70
178	274	428	92.34	1.20	0.73	-5.00	0.68	-3.30
179	285	428	90.74	1.22	0.70	-5.40	0.61	-4.00
180	261	428	94.18	1.18	0.68	-6.40	0.58	-5.00
181	287	428	90.44	1.22	0.65	-6.40	0.53	-5.00
182	326	428	84.16	1.33	1.12	1.70	0.96	-0.20
183	322	428	84.86	1.31	1.15	2.00	0.99	0.00
184	335	428	82.53	1.37	1.09	1.20	0.90	-0.50
185	327	428	83.98	1.33	1.07	0.90	0.87	-0.80
186	322	428	84.86	1.31	1.07	1.00	0.91	-0.60
187	327	428	83.98	1.33	1.10	1.30	0.98	-0.10
188	334	428	82.71	1.36	1.07	1.00	0.86	-0.80
189	327	428	83.98	1.33	1.09	1.30	0.97	-0.10
190	336	428	82.34	1.37	1.04	0.50	0.76	-1.40
191	325	428	84.33	1.32	1.07	1.00	0.85	-0.90
192	308	428	87.19	1.27	1.13	1.90	0.97	-0.20
193	317	428	85.71	1.30	1.08	1.20	0.93	-0.40
194	315	428	86.04	1.29	1.12	1.80	0.96	-0.20
195	319	428	85.37	1.30	1.09	1.30	0.92	-0.50
196	307	428	87.35	1.27	1.17	2.50	1.11	0.90
197	284	428	90.89	1.22	1.23	3.50	1.26	2.20
198	327	428	83.98	1.33	1.08	1.20	0.88	-0.70
199	323	428	84.68	1.32	1.10	1.40	0.91	-0.60
200	319	428	85.37	1.30	1.08	1.20	0.93	-0.50
201	312	428	86.54	1.28	1.12	1.80	0.96	-0.30

Supplementary Table 2. *Item fit statistics for each of the VSEEMT items*

ITEM	RAW SCORE	COUNT	MEASURE	MODEL SE	INFIT MNSQ	INFIT ZSTD	OUTFIT MNSQ	OUTFIT ZSTD
1	257	428	42.01	1.08	1.23	5.20	1.44	6.40
2	35	428	74.62	1.83	1.09	0.70	1.94	3.20
3	44	428	71.89	1.66	1.08	0.70	1.76	3.10
4	266	428	40.95	1.09	0.98	-0.30	0.95	-0.80
5	257	428	42.01	1.08	0.98	-0.60	0.97	-0.50
6	355	428	28.27	1.37	1.00	0.10	1.01	0.10
7	275	428	39.87	1.10	0.92	-1.70	0.86	-2.20
8	333	428	32.02	1.25	1.06	1.00	1.12	1.10
9	192	428	49.38	1.06	0.97	-0.80	0.97	-0.50
10	181	428	50.63	1.07	1.18	4.10	1.24	3.90
11	145	428	54.89	1.11	1.10	2.20	1.22	2.80
12	156	428	53.55	1.09	1.34	7.10	1.48	6.20
13	242	428	43.74	1.07	0.94	-1.60	0.90	-1.80
14	328	428	32.79	1.23	0.99	-0.20	0.93	-0.60
15	226	428	45.55	1.06	0.98	-0.60	0.97	-0.50
16	283	428	38.89	1.11	0.98	-0.50	0.97	-0.30
17	43	428	72.17	1.67	0.98	-0.10	1.38	1.70
18	286	428	38.52	1.12	1.04	0.80	1.04	0.60
19	273	428	40.11	1.10	0.85	-3.40	0.78	-3.50
20	265	428	41.07	1.09	0.83	-4.10	0.77	-4.00
21	264	428	41.19	1.09	0.83	-4.10	0.77	-3.90
22	291	428	37.89	1.13	0.94	-1.20	0.90	-1.30
23	273	428	40.11	1.10	1.02	0.40	1.02	0.30
24	121	428	57.97	1.16	0.99	-0.10	0.96	-0.40
25	96	428	61.56	1.24	0.98	-0.30	0.94	-0.50
26	268	428	40.71	1.09	1.01	0.30	1.02	0.30
27	161	428	52.96	1.09	0.98	-0.40	0.94	-1.00
28	331	428	32.33	1.24	0.83	-2.70	0.68	-3.20
29	204	428	48.03	1.06	0.85	-4.10	0.81	-3.90
30	252	428	42.59	1.08	0.80	-5.10	0.76	-4.40
31	229	428	45.21	1.06	0.92	-2.10	0.89	-2.10
32	239	428	44.08	1.07	1.00	0.10	1.00	0.10
33	214	428	46.90	1.06	0.86	-3.90	0.84	-3.20
34	127	428	57.18	1.15	0.93	-1.50	0.85	-1.90
35	11	428	87.42	3.10	1.08	0.40	1.68	1.40
36	149	428	54.40	1.10	1.05	1.10	1.11	1.60
37	50	428	70.33	1.57	1.06	0.60	1.35	1.70
38	38	428	73.65	1.76	1.08	0.70	1.07	0.40
39	274	428	39.99	1.10	0.95	-1.10	0.92	-1.20
40	125	428	57.44	1.15	0.96	-0.70	0.91	-1.10
41	158	428	53.32	1.09	1.01	0.20	0.96	-0.60
42	283	428	38.89	1.11	0.95	-1.10	0.95	-0.70
43	108	428	59.78	1.20	1.09	1.50	1.23	2.20
44	8	428	90.77	3.61	0.95	0.00	0.56	-0.80
45	223	428	45.89	1.06	1.16	3.90	1.19	3.40
46	218	428	46.45	1.06	1.15	3.80	1.22	3.90